Molecular CO(1-0) gas in the $z \sim 2$ radio galaxy MRC 0152-209

B. H. C. Emonts[1,12], I. Feain[1], M. Y. Mao[2,1,3], R. P. Norris[1], G. Miley[4], R. D. Ekers[1], M. Villar-Martín[5], H. J. A. Röttgering[4], E. M. Sadler[6], G. Rees[7,1], R. Morganti[8,9], D. J. Saikia[10], T. A. Oosterloo[8,9], J. B. Stevens[1], C. N. Tadhunter[11]

[1] *CSIRO Astronomy and Space Science, Australia Telescope National Facility, PO Box 76, Epping NSW, 1710, Australia*

[2] *School of Mathematics and Physics, University of Tasmania, Private Bag 37, Hobart, 7001, Australia*

[3] *Australian Astronomical Observatory, PO Box 296, Epping, NSW, 1710, Australia*

[4] *Leiden Observatory, University of Leiden, P.O. Box 9513, 2300 RA Leiden, Netherlands*

[5] *Instituto de Astrofísica de Andalucía (CSIC), Aptdo. 3004, Granada, Spain*

[6] *School of Physics, University of Sydney, NSW 2006, Australia*

[7] *School of Physics, Astronomy and Mathematics, University of Hertfordshire, College Lane, Hatfield AL10 9AB*

[8] *Netherlands Institute for Radio Astronomy, Postbus 2, 7990 AA Dwingeloo, the Netherlands*

[9] *Kapteyn Astronomical Institute, University of Groningen, P.O. Box 800, 9700 AV Groningen, the Netherlands*

[10] *National Centre for Radio Astrophysics, TIFR, Pune University Campus, Post Bag3, Pune 411 007, India*

[11] *Department of Physics and Astronomy, University of Sheffield, Sheffield S3 7RH, UK*

[12] *Bolton Fellow*

bjorn.emonts@csiro.au

ABSTRACT

We report the detection of molecular CO(1-0) gas in the high-z radio galaxy MRC 0152-209 ($z = 1.92$) with the Australia Telescope Compact Array Broadband Backend (ATCA/CABB). This is the third known detection of CO(1-0) in a high-z radio galaxy to date. CO(1-0) is the most robust tracer of the overall molecular gas content (including the wide-spread, low-density and subthermally excited component), hence observations of CO(1-0) are crucial for studying galaxy evolution in the Early Universe. We derive $L'_{\rm CO} = 6.6 \pm 2.0 \times 10^{10}$ K km s^{-1} pc^2 for MRC 0152-209, which is comparable to that derived from CO(1-0) observations of several high-z submillimeter and starforming BzK galaxies. The CO(1-0) traces a total molecular hydrogen mass of $M_{\rm H2} = 5 \times 10^{10}$ ($\alpha_{\rm x}/0.8$) M$_\odot$. MRC 0152-209 is an infra-red bright radio galaxy, in which a large reservoir of cold molecular gas has not (yet) been depleted by star formation or radio source feedback. Its compact radio source is reliably detected at 40 GHz and has a steep spectral index of $\alpha = -1.3$ between 1.4 and 40 GHz ($4 - 115$ GHz in the galaxy's rest-frame). MRC 0152-209 is part of an ongoing systematic ATCA/CABB survey of CO(1-0) in high-z radio galaxies between $1.7 < z < 3$.

Subject headings: Galaxies: active — Galaxies: evolution — Galaxies: high-redshift — Galaxies: individual (MRC 0152-209) — Galaxies: ISM — Radio lines: ISM

1. Introduction

High-redshift radio galaxies (HzRGs; $L_{\rm 500MHz} > 10^{27}$ W Hz^{-1}) are among the most massive galax-

ies in the early Universe (Miley & De Breuck 2008). They are typically surrounded by rich proto-cluster environments and are believed to be the ancestors of early-type central-cluster galaxies (e.g. Venemans et al. 2007). HzRGs are in an active stage of their evolution, with powerful radio jets emanating from a massive central black-hole. These radio jets vigorously interact with their surrounding environment (e.g. Humphrey et al. 2006) and serve as beacons for tracing the faint host galaxy and surrounding proto-cluster. This makes HzRGs among the best studied high-z objects and ideal laboratories for investigating both the formation and evolution of galaxies/clusters as well as the relationship between early star formation and AGN activity.

A crucial component in the evolutionary studies of HzRGs and their associated star formation processes is a detailed knowledge about the content and properties of the molecular gas. The most abundant molecule, molecular hydrogen or H_2, has strongly forbidden rotational transitions and is virtually invisible, except when it is shocked or heated to high temperatures. An excellent tracer for H_2 gas is carbon monoxide or CO, which emits strong rotational transition lines that occur primarily through collisions with H_2, even at relatively low densities (e.g. Solomon & Vanden Bout 2005). Brown & Vanden Bout (1991) were the first to observe ^{12}CO (referred to as CO in this paper) beyond $z = 2$.

During that same decade, intensive searches failed to detect CO in HzRGs (Evans et al. 1996; van Ojik et al. 1997a). Since then, CO emission has been detected in individual studies of powerful radio galaxies between $z \sim 2-5$ (see reviews by Solomon & Vanden Bout 2005; Miley & De Breuck 2008, and Sect. 4.2 for individual references). In some cases the CO has been resolved on scales of several tens of kpc (e.g. Papadopoulos et al. 2000).

Despite these results, two major limitations to systematic searches for CO in HzRGs have been the very limited velocity coverage of existing mm-spectrometers (often not much wider than the velocity range of the CO gas and/or the accuracy of the redshift) and the fact that most observatories can only target the higher rotational transitions of CO at high-z. While these higher CO transitions trace the dense and thermally excited gas (such

as that in the nuclear starburst/AGN region), Papadopoulos et al. (2000, 2001) suggest that more widely distributed reservoirs of less dense and sub-thermally excited gas could be largely missed by these observations and could thus more easily be detected in the lower transitions than often assumed (see also e.g. Dannerbauer et al. 2009; Carilli et al. 2010; Ivison et al. 2011, and references therein). The luminosity of the ground transition, CO(1-0), is least affected by the excitation conditions of the gas. Therefore, observations of CO(1-0) are crucial for deriving the most accurate estimates of the overall molecular gas content in high-z galaxies.

Ongoing developments in broadband correlators are overcoming the above mentioned limitations. As we discussed in Emonts et al. (2011), the upgrade of the Australia Telescope Compact Array (ATCA) with the 2×2 GHz Compact Array Broadband Backend (CABB; Wilson et al. 2011) now allows searching for CO(1-0) across the southern hemisphere. We are currently in the process of observing an unbiased sample of HzRGs from the Molonglo Reference Catalogue (McCarthy et al. 1990) in CO(1-0) with the ATCA/CABB 7mm system between $1.7 < z < 3$.

In this Letter, we present the detection of CO(1-0) emission in one of our sample sources, MRC 0152-209 (z=1.92). MRC 0152-209 is a radio galaxy with a disturbed optical morphology (Pentericci et al. 2001). It is bright in the near- and mid-IR (Seymour et al. 2007; De Breuck et al. 2010), detected in Lyα (McCarthy et al. 1991) and has a compact radio source (1.6 arcsec/13 kpc in diameter; Pentericci et al. 2000).

Throughout this paper, we assume $H_0 = 71 \, \mathrm{km \, s^{-1} \, Mpc^{-1}}$, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$, corresponding to an angular distance scale of 8.3 kpc arcsec^{-1} and luminosity distance $D_L = 14571$ Mpc for MRC 0152-209 (following Wright 2006).[1]

2. Observations

MRC 0152-209 was observed on 25 & 26 August and 28 & 29 September 2010 with ATCA/CABB in the most compact hybrid H168 and H75 array configurations. The total effective on-source integration time was 15.5h (with 45% of our overall

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[1]See http://www.astro.ucla.edu/~wright/CosmoCalc.html

observing time spent on overheads and calibration). We used the coarsest spectral-line CABB mode (2×2 GHz bandwidth; 1 MHz resolution) and centered both 2 GHz observing bands around 39.476 GHz[2], the frequency that corresponds to the CO(1-0) line ($\nu_{rest} = 115.2712$ GHz) Doppler-shifted to $z = 1.92$. We observed only above $30°$ elevation and during atmospheric conditions in which there was no significant phase decorrelation of the signal, with $T_{sys} = 50 - 80$K during the various runs. Short (2 min) scans were made on the nearby strong calibrator PKS B0130-171 ($S_{40\ GHz} \approx 2.3$ Jy beam^{-1}) roughly every 10 minutes in order to derive frequent gain- and bandpass-calibration solutions, both of which were interpolated in time and applied to the data of MRC 0152-209. We observed Uranus when it was at roughly the same elevation as PKS B0130-171 in order to flux calibrate our data with an accuracy of 30%. Details on the calibration strategy (using MIRIAD) and flux calibration uncertainties are described in Emonts et al. (2011).

We used multi-frequency synthesis to obtain a continuum image (with robustness = +1; Briggs 1995), which we subsequently cleaned. We then separated the spectral-line from the continuum data with a linear fit to the line-free channels in the uv-domain before Fourier transforming the data into a line-data cube (robustness = +1). The velocity axis was translated to match the optical barycentric rest-frame velocity at the redshift of MRC 0152-209 ($z = 1.92$; De Breuck et al. 2000). The spatial resolution of our final data is 9.80×7.09 arcsec (PA = 89.8°), with a velocity resolution in the line data of 7.6 km s^{-1} per 1 MHz channel at 39.476 GHz across an effective velocity range of ~ 15000 km s^{-1}. The noise is 58 μJy beam^{-1} in the continuum image and 0.47 mJy beam^{-1} per 1 MHz channel in the line data. For the data analysis presented in this paper we have binned the line data to 40 km s^{-1} wide channels and subsequently applied a hanning smooth, resulting in an effective velocity resolution of 80 km s^{-1} and a noise level of $\sigma = 0.16$ mJy beam^{-1} chan^{-1}.

[2]The actual central frequency of the bands was chosen to be 39.9 GHz, because channels were missing in the first half of each band at the time of our observations. Only one of the observing bands was used in the final data analysis (see also Emonts et al. 2011).
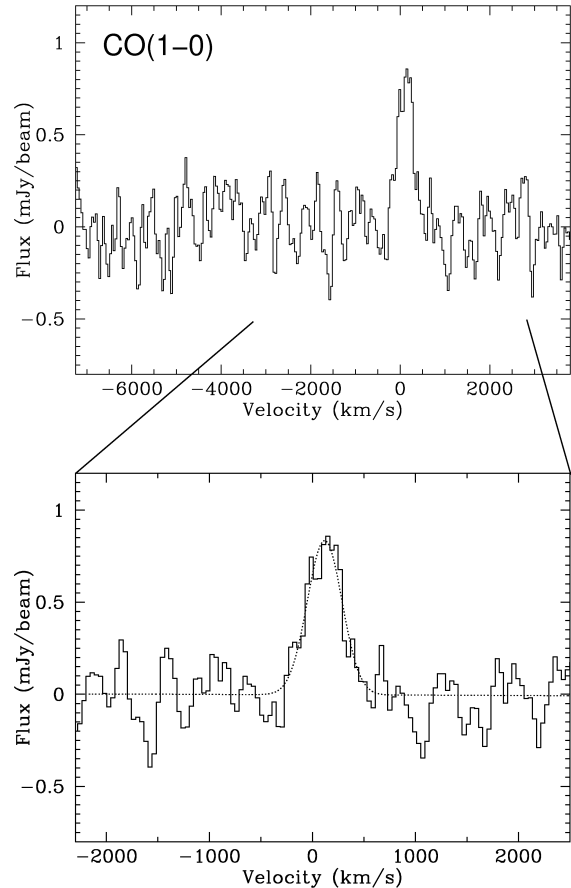
Fig. 1.— *Top:* CO(1-0) spectrum of MRC 0152-209 against the central host galaxy (extracted by averaging the central four pixels of the binned line data, Sect. 2). *Bottom:* zoom-in of the CO(1-0) spectrum. The dotted line show a Gaussian fit.

3. Results

3.1. CO(1-0)

Figure 1 shows the spectrum of CO(1-0) against the central region of MRC 0152-209. From fitting a Gaussian to this profile, we derive that the CO(1-0) signal has a peak flux density of $S_{CO} = 0.84 \pm 0.25$ mJy beam^{-1} [3] and FWHM $= 397 \pm 37$ km s^{-1}. The CO(1-0) signal peaks at a redshift of $z_{CO} = 1.9212 \pm 0.0002$, in agreement with the optical redshift of $z = 1.92$ (McCarthy et al. 1991; De Breuck et al. 2000). Figure 2 *(left)* shows

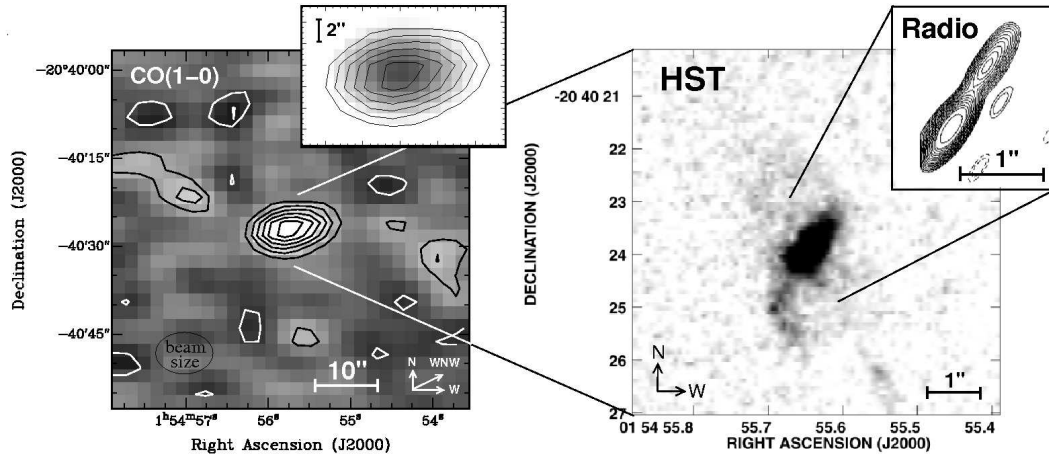[3]The error reflects the accuracy of the flux calibration (Sect. 2)

Fig. 2.— *Left:* total intensity image of the CO(1-0) signal of Fig. 1 (see text for details). Contour levels: -3, -2 (white); 2, 3, 4, 5, 6, 7 (black) σ, corresponding to L'_{CO} = -2.5, -1.7 (white); 1.7, 2.5, 3.3, 4.2, 5.0, 5.8 $\times 10^{10}$ K km s^{-1} pc^2. The inset shows the same CO contours overlaid onto the unresolved 40 GHz ATCA radio continuum (grey-scale). *Right:* HST/NICMOS image from Pentericci et al. (2001), showing the disturbed host-galaxy morphology. The inset show the 8.2 GHz radio continuum from Pentericci et al. (2000).

a total intensity map of the CO(1-0) line integrated over the channels in which the line was detected. The integrated CO(1-0) signal is detected at the 8σ level and $\int_v S_{CO} \delta v = 0.37 \pm 0.11$ Jy beam^{-1} × km s^{-1}. There is a tentative indication from Figure 2 *(left)* that the CO(1-0) emission is marginally resolved in west-north-western (WNW) direction. This would mean that the CO(1-0) gas is distributed on scales larger than the major beam axis, which corresponds to ~81 kpc. Observations at higher spatial resolution are in progress to verify this.

The CO(1-0) emission-line luminosity can be calculated following Solomon & Vanden Bout (2005, and references therein):

$$L'_{CO} = 3.25 \times 10^7 (\frac{\int_v S_{CO} \delta v}{\text{Jy km/s}})(\frac{D_L}{\text{Mpc}})^2(\frac{\nu_{rest}}{\text{GHz}})^{-2}(1+z)^{-1},$$
(1)

with L'_{CO} expressed in K km s^{-1} pc^2. For MRC 0152-209, $L'_{CO} = 6.6 \pm 2.0 \times 10^{10}$ K km s^{-1} pc^2.

3.2. Radio continuum

The radio continuum emission of MRC 0152-209 is unresolved in our ATCA observations and has a flux of $S_{39.9\text{GHz}} = 5.1 \pm 1.5$ mJy. Using our 40 GHz flux and 8.2, 4.7 and 1.4 GHz data from

Pentericci et al. (2000), the spectral index can be fitted with a power-law of the form $S_\nu \propto \nu^\alpha$ from ~1.4 to 40 GHz (4 − 115 GHz in the galaxy's rest-frame; Fig. 3). This yields a steep high-frequency spectral index of $\alpha_{1.4\,\text{GHz}}^{40\,\text{GHz}} \approx -1.3$. Data obtained from surveys conducted below 1 GHz suggest a flattening of the spectrum at low frequencies, possibly fitted more accurately by a second order polynomial rather than a single power-law (Fig. 3). Additional measurements are required to determine this reliably, but this is beyond the scope of the current paper.

4. Discussion

4.1. Molecular gas and star formation

From the CO(1-0) luminosity we can estimate the mass of molecular gas in MRC 0152-209 by adopting a standard conversion factor $\alpha_x = M_{H2}/L'_{CO}$ [$M_\odot$ (K km s^{-1} pc^2)$^{-1}$] (where M_{H2} includes a helium fraction; e.g. Solomon & Vanden Bout 2005). In this paper, we use $\alpha_x = 0.8$ $M_\odot$ (K km s^{-1} pc^2)$^{-1}$ found by Downes & Solomon (1998) for ultra-luminous infra-red galaxies (ULIRGs). This also agrees with $\alpha_x = 0.8 - 1.6$ $M_\odot$ (K km s^{-1} pc^2)$^{-1}$ found for high-z sub-millimeter and star forming galax-
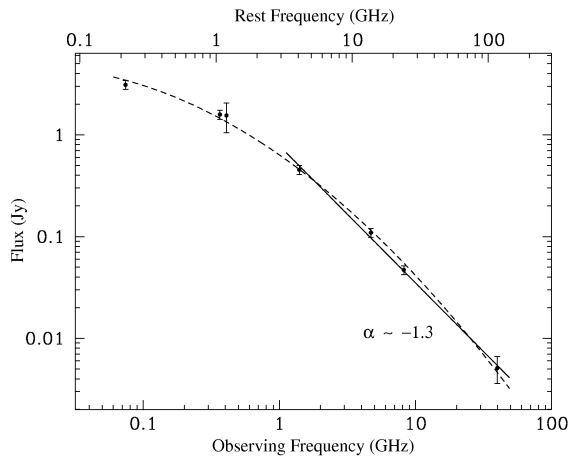
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Fig. 3.— Radio spectral index of MRC 0152-209. Data at 1.4, 4.7 and 8.2 GHz are from Pentericci et al. (2000); the lower frequency data are taken from various surveys listed in the NASA Extra-galactic Database (NED – see http://nedwww.ipac.caltech.edu/). The solid line represents a broken power-law fit ($F_\nu \propto \nu^\alpha$), the dashed line shows a second order polynomial fit.

ies (Tacconi et al. 2008; Stark et al. 2008). We note, however, that the conversion of CO luminosity into H_2 mass depends on the properties of the gas, such as metallicity and radiation field (e.g. Glover & Mac Low 2011), and that conversion factors as high as of $\alpha_x = 5$ $M_\odot$ (K km s^{-1} pc^2)$^{-1}$ have been derived for molecular clouds in the Milky Way (e.g. Solomon & Barrett 1991). Our assumption of $\alpha_x = 0.8$ $M_\odot$ (K km s^{-1} pc^2)$^{-1}$ thus results in a conservative estimate of the total molecular gas mass in MRC 0152-209 of $M_{H2} = 5 \times 10^{10} M_\odot$.

The 24μm infra-red (IR) flux of MRC 0152-209 ($f_{24\mu m} = 3320 \pm 133$ μJy) is among the highest in a large sample of HzRGs observed with *Spitzer* by De Breuck et al. (2010). At $z = 1.92$, the observed $\lambda = 24$ μm corresponds to $\lambda = 8.2$ μm in the rest-frame, hence from $f_{24\mu m}$ we derive a mono-chromatic rest-frame luminosity of $(\nu L_\nu)_{8.2\mu m}^{\rm rest} = 2.7 \times 10^{12} L_\odot$. When comparing the mid-IR rest-frame colors (De Breuck et al. 2010) with IRAC color diagrams by Stern et al. (2005), MRC 0152-209 falls within the region that is dominated by active galaxies, indicating that a significant fraction of the 8 μm flux may originate from

a hot dusty torus surrounding the central AGN.

Alternatively, part of $(\nu L_\nu)_{8.2\mu m}^{\rm rest}$ may arise from a dust-enshrouded starburst, which peaks in the far-IR (FIR). Evans et al. (2005) show that low-z radio galaxies follow a strong correlation between $L'_{\rm CO}$ and $L_{\rm FIR}$. This trend is also seen among high-z submillimeter galaxies (SMGs; Greve et al. 2005; Ivison et al. 2011) and likely reflects the Schmidth-Kennicutt relation between star formation rates and gas reservoir (Schmidt 1959; Kennicutt 1998). If this correlation is also valid for HzRGs, the CO(1-0) luminosity of MRC 0152-209 implies a FIR luminosity of order $L_{\rm FIR} \sim 5 \times 10^{12}$ $L_\odot$ (Ivison et al. 2011), well in the regime of ULIRGs. Bavouzet et al. (2008) show that the mono-chromatic IR luminosities of starburst-dominated ULIRGs at 8, 24, 70 and 160μm are strongly correlated with the total IR luminosity ($L_{\rm IR} = L_{5-1000\mu m}$), with reliable correlations up to $z \sim 2$. While these correlations may not necessarily be valid in case a significant fraction of $(\nu L_\nu)_{8.2\mu m}^{\rm rest}$ in MRC 0152-209 is AGN related, we argue that they still provide a reliable upper limit to $L_{\rm IR}$, given that a 'starburst-only' scenario will provide the highest possible energy output in the FIR and thus maximize $L_{\rm IR}$. From $(\nu L_\nu)_{8\mu m}^{\rm rest}$ and following Bavouzet et al. (2008, their Equation 6), we therefore estimate that $L_{\rm IR} \lesssim 7.9 \times 10^{12} L_\odot$ for MRC 0152-209.

The upper limit on the dust-to-gas ratio in MRC 0152-209 can then be estimated to be $L_{\rm IR}/L'_{\rm CO} \lesssim 120$, consistent with that of nearby ULIRGs (Solomon et al. 1997). Following Kennicutt (1998), the upper limit on the star formation rate is SFR $\approx \frac{L_{\rm IR}}{5.8 \times 10^9 L_\odot} \lesssim 1362$ $M_\odot$ yr^{-1}. Assuming that the molecular gas in MRC 0152-209 offers a reservoir to sustain this maximum star formation rate, the lower limit on the gas depletion time-scale is $t_{\rm depletion} = \frac{M_{H2}}{\rm SRF} \gtrsim \epsilon^{-1} \cdot 39$ Myr (with $0 \le \epsilon \le 1$ the star formation efficiency). According to models by Mihos & Hernquist (1994), this minimum gas depletion time-scale is comparable to the typical lifetime of a massive burst of star formation during a major merger, which could give the merging system the appearance of a ULIRG for about ~ 50 Myr (although Swinbank et al. (2006) show that for high-z SMGs a starburst age of several 100 Myr is more realistic). It is conceivable that also MRC 0152-209 has undergone a recent merger, given its disturbed optical

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morphology (Pentericci et al. 2001).

Therefore, MRC 0152-209 shares characteristics commonly found among ULIRGs, but its classification remains somewhat ambiguous until the nature of the IR emission and star formation properties are better understood. It is clear, however, that MRC 0152-209 contains a large reservoir of molecular gas that has not (yet) been depleted by vigorous star formation.

4.2. CO(1-0) in HzRGs

The CO(1-0) luminosity of MRC 0152-209 is an order of magnitude larger than that found in nearby radio galaxies (Ocaña Flaquer et al. 2010; Evans et al. 2005), indicating that MRC 0152-209 contains significantly more molecular gas than its low-z counterparts.

Assuming $\alpha_x = 0.8$, the H_2 mass of MRC 0152-209 is of the same order as that derived from CO detections in other HzRGs (Scoville et al. 1997; Papadopoulos et al. 2000, 2001; Alloin et al. 2000; De Breuck et al. 2003a,b, 2005; Greve et al. 2004; Klamer et al. 2005; Ivison et al. 2008; Nesvadba et al. 2009) as well as from a survey of high-z SMGs (Greve et al. 2005). However, most of these CO studies relied on observations of the higher rotational CO transitions, which could underestimate the total mass and spatial extent of the molecular gas (see Sect. 1).

To our knowledge, CO(1-0) detections have been claimed for only two other HzRGs, namely TN J0924-2201 ($z = 5.2$; Klamer et al. 2005) and 4C 60.07 ($z = 3.8$; Greve et al. 2004; Ivison et al. 2008). Both systems contain $M_{H2} \sim 10^{11} M_\odot$. Interestingly, they both are IR-faint objects (De Breuck et al. 2010; Ivison et al. 2008). CO(1-0) observations of four SMGs ($z = 2.2 - 2.5$; Ivison et al. 2011) and three massive star-forming disk (BzK) galaxies ($z \sim 1.5$; Aravena et al. 2010) reveal CO(1-0) luminosities comparable to that of MRC 0152-209. *CO(1-0) observations of larger and unbiased samples of various types of high-z galaxies are necessary to investigate and compare the molecular gas content in these systems in a systematic way.*

4.2.1. CO(1-0) and radio source properties

The radio source in MRC 0152-209 is fairly compact (13 kpc) and not reaching beyond the op-

tical boundaries of the host galaxy (Pentericci et al. 2000, 2001). Based on a CO(3-2) detection in the outer part of the Lyα halo that surrounds the $z = 2.6$ radio galaxy TXS 0828+193, Nesvadba et al. (2009) speculate that large amounts of dense gas (and perhaps dust) may be present in the halos of HzRGs at radii that are not yet affected by mechanical heating from the radio source. This would be in agreement with studies of the neutral gas in HzRGs by van Ojik et al. (1997b), who find that strong H I absorption is predominantly associated with small (< 50kpc) radio sources. It will be particularly interesting to investigate whether the CO(1-0) gas, i.e., the part of the observable molecular gas that is least affected by excitation and heating, shows a similar trend with radio source size, or whether *on average* HzRGs are fainter in CO(1-0) than their radio-quiet high-z counterparts.

Besides MRC 0152-209, we recently published a tentative CO(1-0) detection with ATCA/CABB in the HzRG MRC 0943-242 (Emonts et al. 2011). This tentative CO(1-0) detection is found in the outer part of the Lyα halo that surrounds MRC 0943-242 (i.e. beyond the $\sim$15 kpc radius of the radio source). Regarding the other two known HzRGs with CO(1-0) detections (Sect. 4.2), TN J0924-2201 also contains a compact radio source (Klamer et al. 2005), while for 4C 60.07 the radio source is extended, but the CO(1-0) most likely represents tidal debris from a galaxy-galaxy interaction ($z = 3.8$; Ivison et al. 2008).

In a forthcoming paper, we will present result of our ongoing systematic CO(1-0) survey of a larger sample of HzRG with ATCA/CABB. This will allow further investigation into possible connections between radio-AGN activity and the cold molecular gas properties of HzRGs.

5. Conclusions

We have presented a robust detection of CO(1-0) in the high-z radio galaxy MRC 0152-209 ($z = 1.92$), tracing a molecular gas mass of $M_{H2} = 5 \times 10^{10} (\alpha_x/0.8) M_\odot$. MRC 0152-209 is an IR-bright radio galaxy that contains a large reservoir of cold molecular gas that has not (yet) been depleted by star formation or radio source feedback.

CO(1-0) is the most robust tracer of molecular gas (including the wide-spread, low-density and

sub-thermally excited component) in high-z galaxies. The search for CO(1-0) in HzRGs at observing frequencies below 50 GHz with the ATCA and EVLA will be a crucial complement to surveys of the higher CO transitions with ALMA.

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